

# Rare Higgs three body decay induced by top-Higgs FCNC coupling in the littlest Higgs Model with T-parity

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## Abstract

Motivated by the search for flavor-changing neutral current (FCNC) top quark decays at the LHC, we calculate rare Higgs three body decay  $H \rightarrow Wbc$  induced by top-Higgs FCNC coupling in the littlest Higgs model with T-parity(LHT). We find that the branching ratios of  $H \rightarrow Wbc$  in the LHT model can reach  $\mathcal{O}(10^{-7})$  in the allowed parameter space.

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## I. INTRODUCTION

The discovery of a Higgs-like resonance near 125 GeV [1] at the LHC is a great triumph for theoretical and experimental particle physics. So far, most measurements of this new particle are consistent with the Standard Model (SM) prediction, but the experimental investigation of this new particle has only just begun. It is not impossible that more in-depth studies will reveal its non-SM properties.

Compared with the normal decay modes, the flavour-changing neutral current (FCNC) decays are highly suppressed in the SM due to the Glashow-Iliopoulos-Maiani (GIM) mechanism[2]. So, any large enhancements in these branching ratios will be smoking-gun signals beyond the SM.

As the heaviest known elementary particle, the top quark is widely speculated to be sensitive to the electroweak symmetry breaking (EWSB) mechanism and new physics at TeV-scale. An interesting possibility is the presence of FCNC interactions between the Higgs boson and the top quark. This interaction not only participate in the top quark FCNC decays[3], but also participate in the Higgs FCNC decays[4].

Except for the dominant decay mode  $H \rightarrow b\bar{b}$ , the so called below-threshold decay modes induced by the  $HVV(V = W; Z)$  couplings are also very important, where the decay  $H \rightarrow VV$  with one (or two)  $V$ 's being off-shell and decaying to fermions. In some new physics, the decay mode of Higgs bosons is much richer and 3-body decays may be even more important. Now, almost all Higgs boson decay modes have been measured at the LHC, but they are plagued by large SM backgrounds. So, the rare Higgs 3-body decays may bring us more surprises. In some new physics models, the GIM suppression can be relaxed and/or new particles can contribute to the loops, so that the top-Higgs FCNC couplings  $tqH$ , especially the  $tcH$  coupling, can be enhanced by orders of magnitude larger than those of the SM[5].

In this paper, we study the rare Higgs 3-body decay  $H \rightarrow Wbc$  induced by top-Higgs FCNC coupling in the littlest Higgs Model with T-parity(LHT). This decay includes the FCNC vertex  $tcH$ , which receives the contribution from the new T-odd gauge bosons and T-odd fermions. The results of this process will help to test the SM and probe the LHT model.

The paper is organized as follows. In Sec.II we give a brief review of the LHT model

related to our work. In Secs.III we calculate the rare Higgs 3-body decay  $H \rightarrow Wbc$  induced by top-Higgs FCNC coupling in unitary gauge under current constraints. Finally, we draw our conclusions in Sec.IV.

## II. A BRIEF REVIEW OF THE LHT MODEL

The LHT model is based on an  $SU(5)/SO(5)$  non-linear  $\sigma$  model[6]. At the scale  $f \sim \mathcal{O}$  (TeV), the  $SU(5)$  global symmetry is broken down to  $SO(5)$  by the vacuum expectation value (VEV) of the  $\sigma$  field,  $\Sigma_0$ , given by

$$\Sigma_0 = \langle \Sigma \rangle = \begin{pmatrix} \mathbf{0}_{2 \times 2} & 0 & \mathbf{1}_{2 \times 2} \\ 0 & 1 & 0 \\ \mathbf{1}_{2 \times 2} & 0 & \mathbf{0}_{2 \times 2} \end{pmatrix}. \quad (1)$$

After the global symmetry is broken, there arise 14 Goldstone bosons(GB) which are described by the “pion” matrix  $\Pi$ . Then the kinetic term for the GB matrix can be expressed in the standard non-linear sigma model formalism as

$$\Sigma = e^{i\Pi/f} \Sigma_0 e^{i\Pi^T/f} \equiv e^{2i\Pi/f} \Sigma_0. \quad (2)$$

The  $\sigma$  field kinetic Lagrangian is given by

$$\mathcal{L}_K = \frac{f^2}{8} \text{Tr} |D_\mu \Sigma|^2, \quad (3)$$

with the  $[SU(2) \otimes U(1)]^2$  covariant derivative defined by

$$D_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^2 [g_j W_{j\mu}^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) + g'_j B_{j\mu} (Y_j \Sigma + \Sigma Y_j^T)], \quad (4)$$

where  $W_j^\mu = \sum_{a=1}^3 W_j^{\mu a} Q_j^a$  and  $B_j^\mu = B_j^\mu Y_j$  are the heavy  $SU(2)$  and  $U(1)$  gauge bosons, with  $Q_j^a$  and  $Y_j$  the gauge generators,  $g_j$  and  $g'_j$  are the respective gauge couplings.

The VEV  $\Sigma_0$  also breaks the gauged subgroup  $[SU(2) \times U(1)]^2$  of the  $SU(5)$  down to the SM electroweak  $SU(2)_L \times U(1)_Y$ . At  $\mathcal{O}(v^2/f^2)$  in the expansion of the Lagrangian (3), the masses of the T-parity partners of the  $W$  boson ( $W_H^\pm$ ),  $Z$  boson ( $Z_H$ ) and photon ( $A_H$ ) after EWSB are given by

$$M_{W_H} = M_{Z_H} = gf(1 - \frac{v^2}{8f^2}), \quad M_{A_H} = \frac{g'f}{\sqrt{5}}(1 - \frac{5v^2}{8f^2}) \quad (5)$$

where  $g$  and  $g'$  denote the SM  $SU(2)$  and  $U(1)$  gauge couplings, respectively.  $v$  represents the VEV of the Higgs doublet, which is related to the SM Higgs VEV  $v_{SM} = 246\text{GeV}$  through the following formula:

$$v = \frac{f}{\sqrt{2}} \arccos \left( 1 - \frac{v_{SM}^2}{f^2} \right) \simeq v_{SM} \left( 1 + \frac{1}{12} \frac{v_{SM}^2}{f^2} \right). \quad (6)$$

In the quark sector, the T-odd mirror partners for each SM quark are added to preserve the T-parity. The up and down-type mirror quarks can be denoted by  $u_H^i$  and  $d_H^i$ , where  $i(= 1, 2, 3)$  is the generation index. One can write down a Yukawa interaction to give masses to the mirror quarks

$$\mathcal{L}_{\text{mirror}} = -\kappa_{ij} f (\bar{\Psi}_2^i \xi + \bar{\Psi}_1^i \Sigma_0 \Omega \xi^\dagger \Omega) \Psi_R^j + h.c. \quad (7)$$

After the EWSB, their masses up to  $\mathcal{O}(v^2/f^2)$  are given by

$$m_{d_H^i} = \sqrt{2}\kappa_i f, \quad m_{u_H^i} = m_{d_H^i} \left( 1 - \frac{v^2}{8f^2} \right) \quad (8)$$

where  $\kappa_i$  are the eigenvalues of the mass matrix  $\kappa$ .

Under T-parity, in order to cancel the large radiative correction to Higgs mass parameter induced by top quark, an additional T-even heavy quark  $T^+$  and its T-odd mirror partner  $T^-$  are introduced. Their masses are given by

$$m_{T^+} = \frac{f}{v} \frac{m_t}{\sqrt{x_L(1-x_L)}} \left[ 1 + \frac{v^2}{f^2} \left( \frac{1}{3} - x_L(1-x_L) \right) \right] \quad (9)$$

$$m_{T^-} = \frac{f}{v} \frac{m_t}{\sqrt{x_L}} \left[ 1 + \frac{v^2}{f^2} \left( \frac{1}{3} - \frac{1}{2} x_L(1-x_L) \right) \right] \quad (10)$$

where  $x_L$  is the mixing parameter between the top-quark and heavy quark  $T^+$ . This mixing parameter can also be expressed by a ratio  $R = \lambda_1/\lambda_2$  with

$$x_L = \frac{R^2}{1+R^2} \quad (11)$$

where  $\lambda_1$  and  $\lambda_2$  are two dimensionless top quark Yukawa couplings.

When the mass matrix  $\sqrt{2}\kappa_{ij}f$  is diagonalized by two  $U(3)$  matrices, a new flavor structure can come from the mirror fermions. In the mirror quark sector, the existence of two CKM-like unitary mixing matrices  $V_{Hu}$  and  $V_{Hd}$  is one of the important ingredients. It's worth noting that  $V_{Hu}$  and  $V_{Hd}$  are related through the SM CKM matrix:

$$V_{Hu}^\dagger V_{Hd} = V_{CKM}. \quad (12)$$

Follow Ref.[7], the matrix  $V_{Hd}$  can be parameterized with three angles  $\theta_{12}^d, \theta_{23}^d, \theta_{13}^d$  and three phases  $\delta_{12}^d, \delta_{23}^d, \delta_{13}^d$

$$V_{Hd} = \begin{pmatrix} c_{12}^d c_{13}^d & s_{12}^d c_{13}^d e^{-i\delta_{12}^d} & s_{13}^d e^{-i\delta_{13}^d} \\ -s_{12}^d c_{23}^d e^{i\delta_{12}^d} - c_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{23}^d)} & c_{12}^d c_{23}^d - s_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{12}^d - \delta_{23}^d)} & s_{23}^d c_{13}^d e^{-i\delta_{23}^d} \\ s_{12}^d s_{23}^d e^{i(\delta_{12}^d + \delta_{23}^d)} - c_{12}^d c_{23}^d s_{13}^d e^{i\delta_{13}^d} & -c_{12}^d s_{23}^d e^{i\delta_{23}^d} - s_{12}^d c_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{12}^d)} & c_{23}^d c_{13}^d \end{pmatrix} \quad (13)$$

For the down-type quarks and charged leptons, there are two possible ways to construct the Yukawa interaction, which are denoted as Case A and Case B[8]. At order  $\mathcal{O}(v_{SM}^4/f^4)$ , the corresponding corrections to the Higgs couplings are given by ( $d \equiv d, s, b, l_i^\pm$ )

$$\begin{aligned} \frac{g_{h\bar{d}d}}{g_{h\bar{d}d}^{SM}} &= 1 - \frac{1}{4} \frac{v_{SM}^2}{f^2} + \frac{7}{32} \frac{v_{SM}^4}{f^4} & \text{Case A} \\ \frac{g_{h\bar{d}d}}{g_{h\bar{d}d}^{SM}} &= 1 - \frac{5}{4} \frac{v_{SM}^2}{f^2} - \frac{17}{32} \frac{v_{SM}^4}{f^4} & \text{Case B} \end{aligned} \quad (14)$$

### III. BRANCHING RATIO FOR $H \rightarrow Wbc$ IN THE LHT MODEL

The Feynman diagrams of the tree level  $H \rightarrow W^+ b \bar{c}$  and the rare decay  $H \rightarrow W^+ b \bar{c}$  are shown respectively in Fig.1 and Fig.2, which includes the  $W^+$  and  $W^-$  modes. The rare Higgs decay  $H \rightarrow Wbc$  is mediated by the same Yukawa coupling that leads to the  $t \rightarrow cH$  decay[9], so we show the Feynman diagrams of the LHT one-loop correction to vertex  $V_{tcH}$  in unitary gauge in Fig.3, where the Goldstone bosons do not appear. We can see that the flavor changing interactions between SM quarks and mirror quarks are mediated by the heavy gauge bosons  $W_H^\pm, Z_H, A_H$ . We find that dominant contribution to the branching ratio of the decay  $H \rightarrow Wbc$  is from the interference between the Fig.1 and Fig.2. Each loop diagram is composed of some scalar loop functions [10], which are calculated by using LOOPTOOLS[11].

In our numerical calculations, we take the SM parameters as follows[12]

$$\begin{aligned} G_F &= 1.16637 \times 10^{-5} \text{GeV}^{-2}, \quad \sin^2 \theta_W = 0.231, \quad \alpha_e = 1/128, \quad m_H = 125 \text{GeV}, \\ m_c &= 1.275 \text{GeV}, \quad m_b = 4.18 \text{GeV}, \quad m_t = 173.2 \text{GeV}, \quad M_W = 80.385 \text{GeV}. \end{aligned} \quad (15)$$

The LHT parameters related to our calculations are the scale  $f$ , the mixing parameter  $x_L$ , the Yukawa couplings  $\kappa_i$  of the mirror quarks and the parameters in the matrices  $V_{Hu}, V_{Hd}$ . Due to the weak influence of the mixing parameter  $x_L$ , we take  $x_L = 0.1$  for an

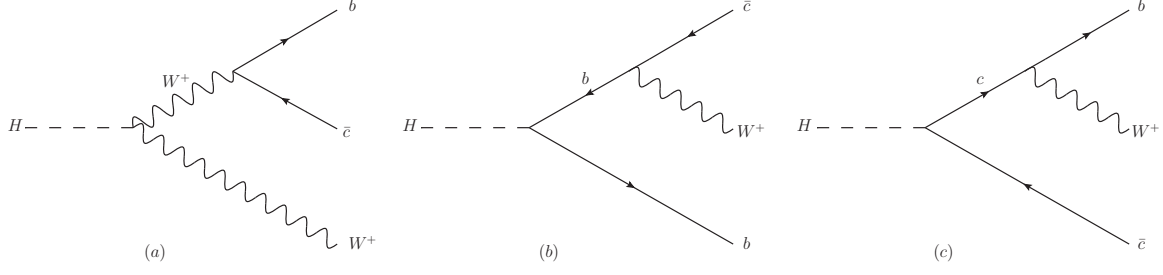


FIG. 1: Feynman diagrams of the decay  $H \rightarrow W^+ b \bar{c}$  at tree level.

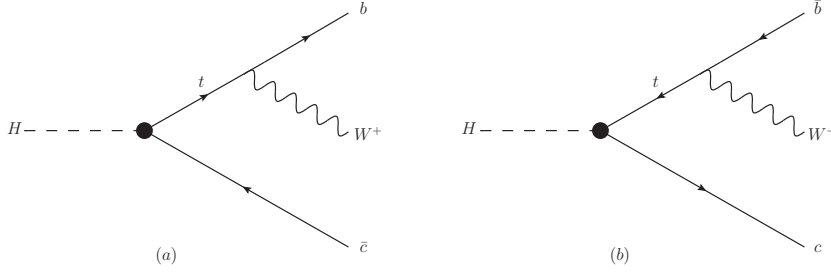


FIG. 2: Feynman diagrams of the rare decay  $H \rightarrow W^+ b \bar{c}$ .

example in our calculations. For the mirror quark masses, we get  $m_{u_H^i} = m_{d_H^i}$  at  $\mathcal{O}(v/f)$  and further assume

$$m_{u_H^1} = m_{u_H^2} = m_{d_H^1} = m_{d_H^2} = M_{12} = \sqrt{2}\kappa_{12}f, \quad m_{u_H^3} = m_{d_H^3} = M_3 = \sqrt{2}\kappa_3f. \quad (16)$$

For the Yukawa couplings, the search for the mono-jet events at the LHC Run-1[14] give the constraint  $\kappa_i \geq 0.6$ . Considering the constraints in Ref.[13], we scan over the free parameters  $f$ ,  $\kappa_{12}$  and  $\kappa_3$  within the following region

$$500\text{GeV} \leq f \leq 2000\text{GeV}, \quad 0.6 \leq \kappa_{12} \leq 3, \quad 0.6 \leq \kappa_3 \leq 3.$$

For the parameters in the matrices  $V_{Hu}$ ,  $V_{Hd}$ , we follow Ref.[15] to consider the two scenarios as follows

- Scenario I:  $V_{Hd} = \mathbf{I}, V_{Hu} = V_{CKM}^\dagger$ ;
- Scenario II:  $s_{23}^d = \frac{1}{\sqrt{2}}, s_{12}^d = s_{13}^d = 0, \delta_{12}^d = \delta_{23}^d = \delta_{13}^d = 0$ .

Furthermore, we will consider the constraint from the global fit of the current Higgs data and the electroweak precision observables (EWPOs)[16]. In Fig.4, we present the

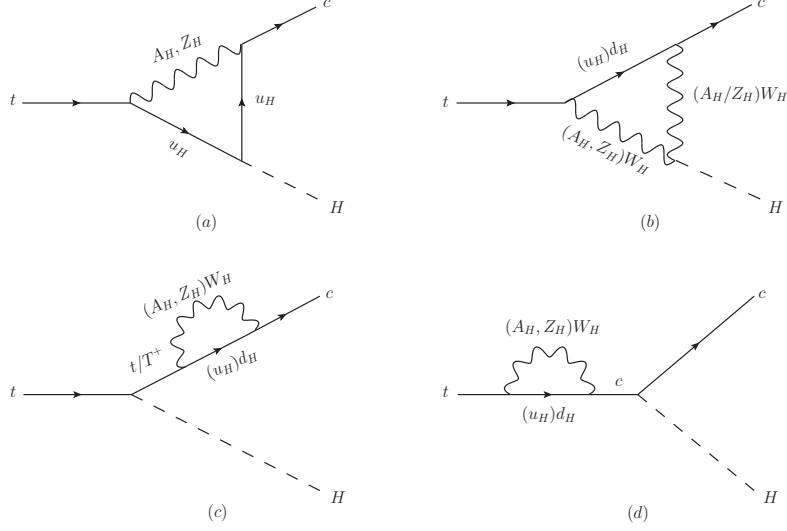


FIG. 3: Feynman diagrams of the LHT one-loop correction to vertex  $V_{tcH}$  in unitary gauge.

excluded regions by the global fit of the Higgs data, EWPOs and  $R_b$  in the  $\kappa \sim f$  plane of the LHT model for Case A and Case B, where the parameter  $R$  is marginalized over. In this global fit, the three generation Yukawa couplings  $\kappa_i$  are considered to be degenerate, which will give a stronger constrain than the nondegenerate case here.

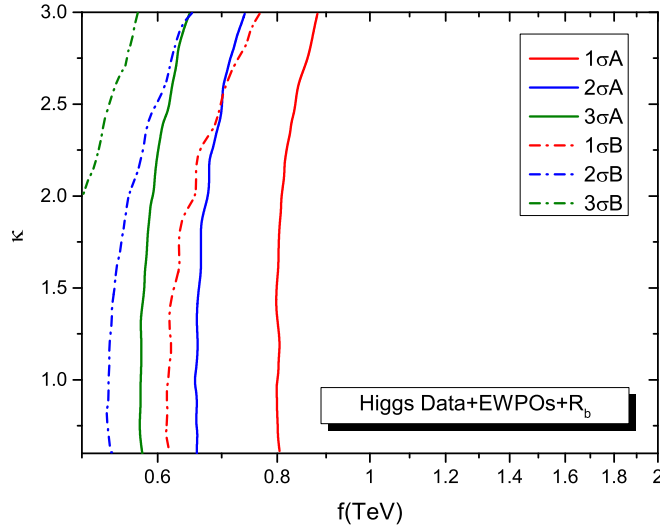


FIG. 4: Excluded regions (above each contour) in the  $\kappa \sim f$  plane of the LHT model for Case A and Case B, where the parameter  $R$  is marginalized over. The solid lines from right to left respectively correspond to  $1\sigma$ ,  $2\sigma$  and  $3\sigma$  exclusion limits for case A, and the dash lines correspond to the case B.

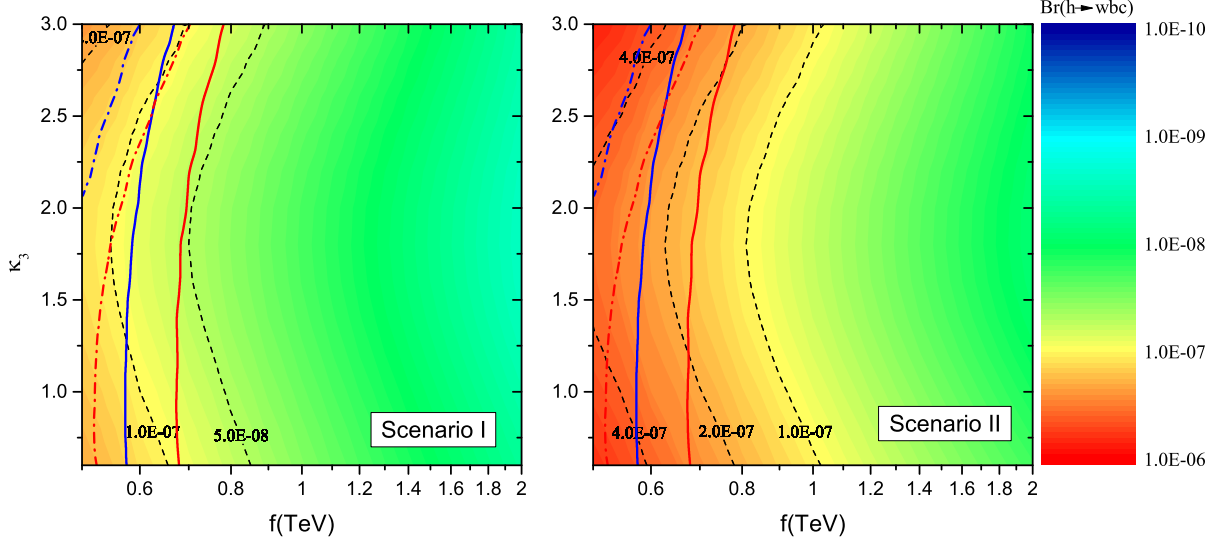


FIG. 5: Branching ratios of  $H \rightarrow Wbc$  in the  $\kappa_3 \sim f$  plane for two scenarios with excluded regions of Case A and Case B, respectively. The red lines and blue lines respectively correspond to  $1\sigma$  and  $2\sigma$  exclusion limits as shown in Fig.4.

In Fig.5, we show the branching ratios of  $H \rightarrow Wbc$  in the  $\kappa_3 \sim f$  plane for two scenarios with excluded regions of Case A and Case B, where the  $W^+$  and  $W^-$  modes have been summed. From the left panel of Fig.4, we can see that the branching ratio of  $H \rightarrow Wbc$  in scenario I can reach  $1 \times 10^{-7}$  at  $2\sigma$  level for Case A. This branching ratio will become larger under the constrain of Case B. From the right panel of Fig.5, we can see that the branching ratio of  $H \rightarrow Wbc$  in scenario II can reach  $4 \times 10^{-7}$  at  $2\sigma$  level, which is three even four times larger than that in scenario I. Comparing the two scenarios, we can find that the enhanced effects come from the large departures from the SM caused by the mixing matrix in scenario II. From the two panels of Fig.5, we can see that the large branching ratios mainly lie in the upper-left and lower-left corners of the contour figures, where the scale  $f$  is small and the Yukawa coupling  $\kappa_3$  is either too small or too large.

According to the Ref.[15], the branching ratio of  $t \rightarrow cH$  is enhanced by the mass splitting between the three generation mirror quarks, the same thing will happen to the branching ratios of  $H \rightarrow Wbc$ . In order to see this dependence, we show the branching ratios of  $H \rightarrow Wbc$  in the  $|M_3 - M_{12}| \sim f$  plane for two scenarios in Fig.6, respectively. We can see that the small branching ratios correspond to the region that has small mass splitting  $|M_3 - M_{12}|$  values. The largest branching ratios lie in the upper-left corners of



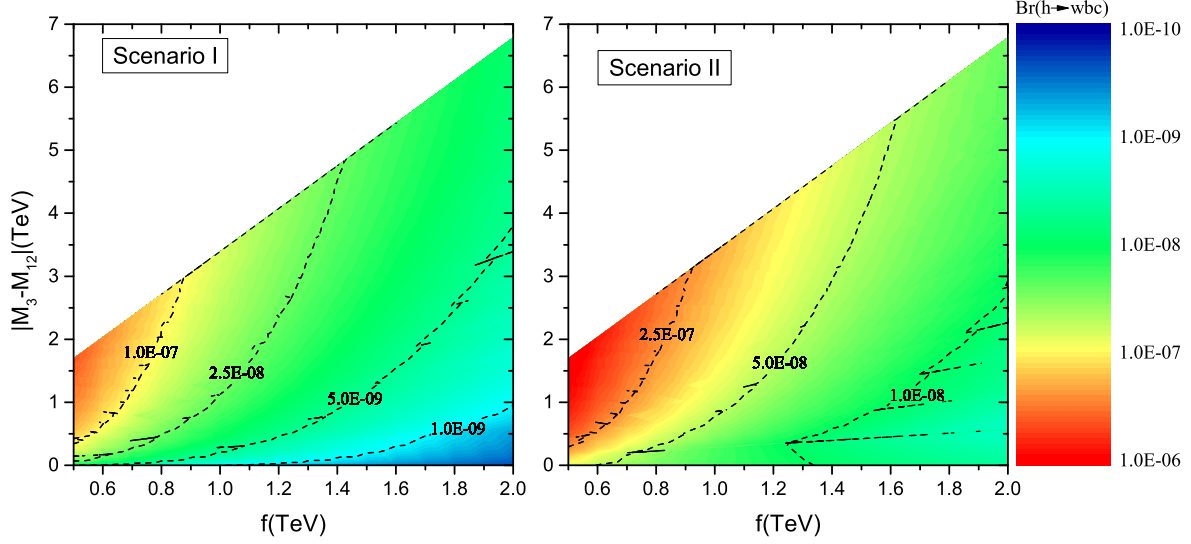


FIG. 6: Branching ratios of  $H \rightarrow Wbc$  in the  $|M_3 - M_{12}| \sim f$  plane for two scenarios.

the contour figure with small  $f$  and  $|M_3 - M_{12}|$  of  $1 \sim 2$  TeV rather than the regions that have the largest  $|M_3 - M_{12}|$ , that is because the branching ratios are suppressed by the high scale  $f$ .

For the observability, the SM decay  $H \rightarrow WW^* \rightarrow Wbc$  is an important irreducible background that will generate the same final state. Due to the off-shell top in the signal decay  $H \rightarrow t^*c \rightarrow Wbc$ , we can use the invariant masses cut  $|M_{Wb} - m_t| > 20$  GeV to isolate the signal. Besides, the  $c$ -jet in our signal comes from the Higgs decay, which usually is harder than that in the SM background  $H \rightarrow WW^* \rightarrow Wbc$ . Thus, we can use the high transverse momentum  $p_T^c$  cut to suppress the background.

Due to the same Yukawa couplings that lead to the  $t \rightarrow cH$  decays, the decays  $H \rightarrow t^*c \rightarrow Wbc$  can be indirectly constrained by ATLAS and CMS searches[17]:  $\text{Br}(H \rightarrow t^*c \rightarrow Wbc) \leq 5.73 \times 10^{-4}$ , where the  $W^+$  and  $W^-$  modes have been summed over. At the LHC, the  $t\bar{t}(\rightarrow WbWb)$  background is undoubtedly a challenge, which will complicate the analysis for detecting the decay  $H \rightarrow t^*c \rightarrow Wbc$ . Given this, the linear collider with clean background may be an ideal place for investigating this process, for example a future muon collider could test the FCNC decay  $t \rightarrow cH$  via Higgs decay  $H \rightarrow t^*c \rightarrow Wbc$  down to values of  $\text{Br}(t \rightarrow cH) \sim 5 \times 10^{-3}$ [18].

## IV. CONCLUSIONS

In this paper, we calculated rare Higgs three body decay  $H \rightarrow Wbc$  induced by top-Higgs FCNC coupling in the LHT model. According to the parameters in the mixing matrices, we considered two scenarios and found that the branching ratio for  $H \rightarrow Wbc$  can reach  $\mathcal{O}(10^{-7})$  in the allowed parameter space.

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